Worldwide glacier mass balance measurements: general trends and first results of the extraordinary year 2003 in Central Europe

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Рассмотрены тренды баланса массы ледников мира, в частности, за 1980–2001 гг. и для чрезвычайно жаркого и сухого лета 2003 г. в Центральной Европе, которое привело к потере 5–10% объема ледников Альп.

Introduction

Worldwide collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the Sixth International Geological Congress in Zürich, Switzerland. It was hoped that long-term glacier observations would give insight into processes of climatic change such as the formation of ice ages. In 1986 the World Glacier Monitoring Service (WGMS) started to maintain and continue the collection of information on ongoing glacier changes, when the two former ICSI services PSFG (Permanent Service on Fluctuations of Glaciers) and TTS/WGI (Temporal Technical Secretary/World Glacier Inventory) were combined [4].

Since its initiation, the goals of international glacier monitoring have evolved and multiplied. Today, the WGMS is integrated into global climate-related observation systems and collects standardized observations on changes in mass, volume, area and length of glaciers with time (glacier fluctuations), as well as statistical information on the distribution of perennial surface ice in space (glacier inventories). Thus, a valuable and increasingly important data basis on glacier changes has been built up over the past century [4].

International assessments such as the periodical reports by the Intergovernmental Panel on Climate Change (IPCC) or the GCOS/GTOS Plan for Terrestrial Climate-related Observation [1] define mountain glaciers as one of the best natural indicators of atmospheric warming with the highest reliability ranking. The Global Terrestrial Network for Glaciers (GTN-G) of the Global Terrestrial Observing System (GTOS), aims at combining (a) in-situ observations with remotely sensed data, (b) process understanding with global coverage and (c) traditional measurements with new technologies by using an integrated and multi-level strategy. This approach, the Global Hierarchical Observing Strategy (GHOST), uses observations in a system of Tiers. These Tiers include extensive glacier mass balance measurements within major climatic zones for improved process understanding and the calibration of numerical models (Tier 2) as well as the determination of regional glacier volume change within major mountain systems using cost-saving methodologies (Tier 3). A network of 60 glaciers representing Tiers 2 and 3 is already established. This data sample closely corresponds to the data compilation published so far by the WGMS with the bi-annual «Glacier Mass Balance Bulletin» [6].

The present contribution gives an overview on presently observed rates of change in worldwide mass balance of mountain glaciers, corresponding trends and regional peculiarities, such as the extremely hot and dry Central European summer of 2003.

Worldwide glacier mass balance observations 1980–2001

Glacier fluctuations result from changes in the mass and energy balance at the Earth's surface. In ablation and temperate firn areas, which predominate at lower latitudes/altitudes and in regions with humid climatic conditions, atmospheric warming causes mainly changes in the mass and geometry of glaciers [3]. Hereby, glacier mass balance is the direct undelayed signal of climatic change, whereas changes in glacier length primarily constitute an indirect, delayed and filtered but also enhanced signal (Fig. 1). Cumulative mass changes lead to ice thickness changes which, in turn, exert a positive feedback on mass balance and at the same time, influence the dynamic redistribution of mass by glacier flow [3].

As mentioned above a network of approximately 60 glaciers with long-term mass balance measurements provides information on presently observed rates of change in glacier mass, corresponding acceleration trends and regional distribution patterns (Fig. 2). Continuous mass balance records for the period 1980–2001 are now available for 30 glaciers for the period 1980–2000 and for 29 glaciers in the year 2000/2001 [6].

These values show that the mean for the period 1990–1999 (-373 mm w.e.) was twice as high as the corresponding mean of the previous decade of 1980–1989 (-188 mm w.e.), with even the year with the maximum mean (1993) yielding a slightly negative mean specific net balance (-9 mm w.e.).

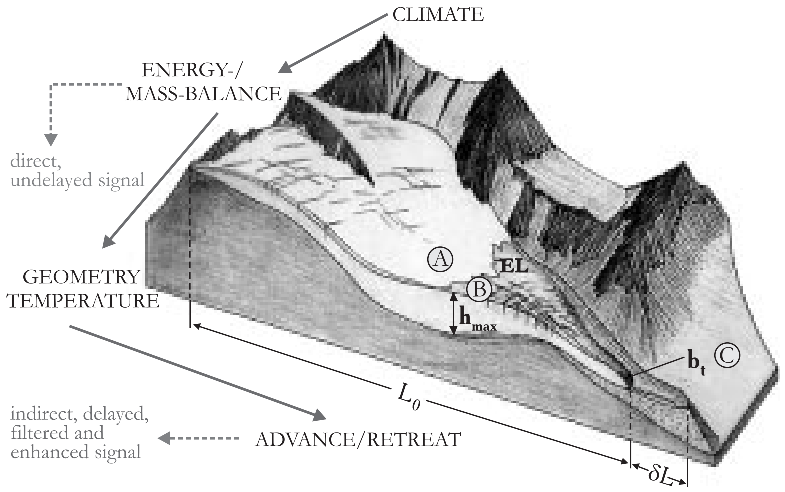

Fig. 1. Schematic plot illustrating the response of glaciers to climatic changes, with glacier mass balance as the direct undelayed signal, and changes in glacier length as an indirect, delayed and filtered but also enhanced signal. Figure modified after [3]

Рис. 1. Схема, иллюстрирующая реакцию ледников на изменения климата, где баланс массы служит прямым немедленным сигналом, а изменения длины ледника — опосредованным, отфильтрованным, хотя и усиленным сигналом, проявляющимся с задержкой. Рисунок с дополнениями по [3]

When considering these values, it has to be taken into account that the mean of all glaciers included in the observed sample is strongly influenced by the large proportion of Alpine and Scandinavian glaciers. Therefore, a mean value is calculated using only one single value (in places averaged) for each of the 9 mountain ranges concerned (Cascades, Alaska, Andes, Svalbard, Scandinavia, Alps, Altai, Caucasus, Tien Shan). Mean specific net balance for the 9 mountain regions during the period 1990–1999 amounts to -482 mm w.e., a value three times higher than the corresponding value for the previous decade from 1980 to1989 (-149 mm w.e.). For the time period from 1980 to 2001 mean specific net balance in these mountain regions averaged roughly -0.3 m w.e. with 20 negative and two positive balance years during these 22 years. The range of extremes observed at individual glaciers during one measurement year is roughly one order of magnitude higher than the mean value of the sample (Fig. 3, a). The significance of the recorded signal, on the other hand, increases with mass balance values cumulated over extended time periods (Fig. 3, b).

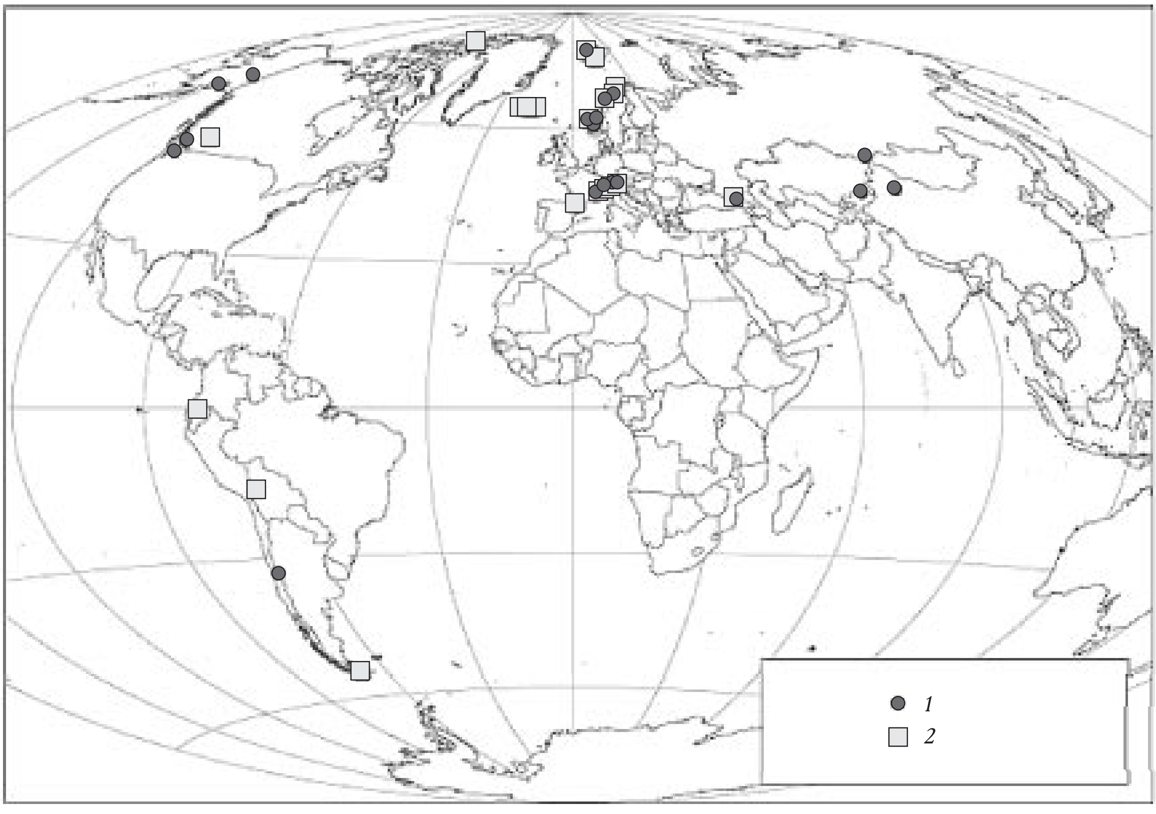

Fig. 2. Current worldwide glacier mass balance monitoring: 1 — glaciers with continuous records from 1980–2001, 2 — glaciers with interrupted or shorter series. Continents and country boundaries provided by ESRI

Рис. 2. Современное состояние мониторинга баланса массы ледников мира: 1 — ледники с непрерывными рядами за 1980–2001 гг., 2 — ледники с пропусками в рядах или более короткими рядами наблюдений. Границы континентов и стран предоставлены ESRI

Table 1

Mean specific net mass balance of 30 glaciers worldwide for the decades 1980–1989 and 1990–1999, and for the period 1980–2001; values in mm w.e.

	Mean 1980–1989	Mean 1990–1999	Mean 1980–2001
Minimum mean	-516	-712	-712
Maximum mean	+112	-9	+112
Mean	-188	-373	-275
Std. Deviation	±243	±234	±245

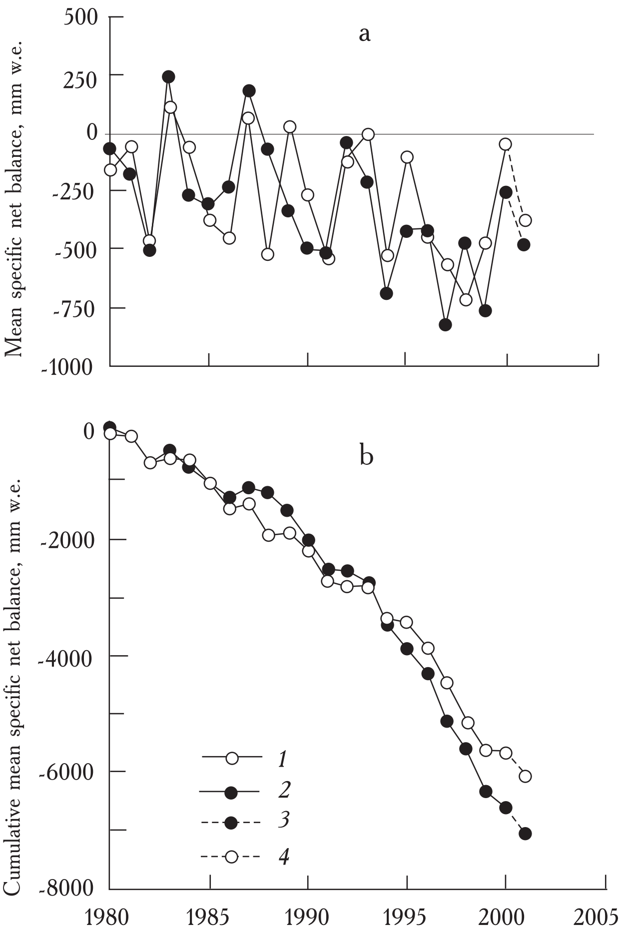

Fig. 3. Evolution with time of the mass balance of 30 glaciers in 9 mountain ranges worldwide (1980–2000), respectively for 29 glaciers in 8 mountain ranges (2001); (a) mean specific net balance, (b) cumulative mean specific net balance [6]: 1, 2 — mean of 30 glaciers and of 9 mountain ranges, 3, 4 — mean of 29 glaciers and 8 mountain ranges, correspondingly

Рис. 3. Изменения во времени баланса массы 30 ледников в 9 горных районах мира (1980–2000) и соответственно для 29 ледников в 8 горных районах (2001); средний удельный баланс (a), кумулятивный средний удельный баланс (b) [6]: 1, 2 — среднее для 30 ледников и 9 хребтов, 3, 4 — среднее для 29 ледников и 8 хребтов, соответственно

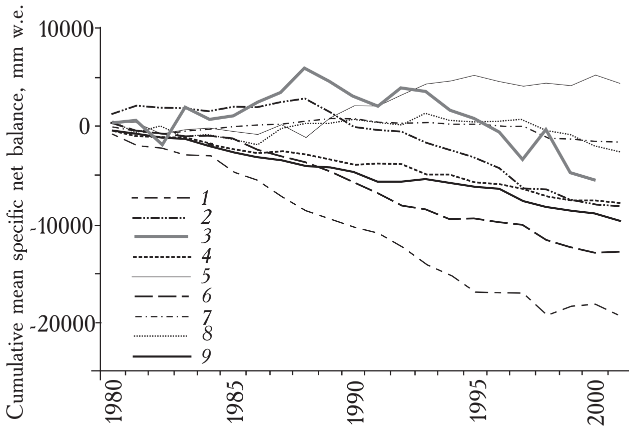

Fig. 4. Cumulative mean specific net balance for 9 different mountain regions for the period 1980–2001: 1 — Cascade Mountains (2 glaciers), 2 — Alaska (2 glaciers), 3 — Andes (1 glacier, 1980–2000), 4 — Svalbard (2 glaciers), 5 — Scandinavian peninsula (8 glaciers), 6 — Alps (9 glaciers), 7 — Altai (3 glaciers), 8 — Caucasus (1 glacier), 9 — Tien Shan (2 glaciers)

Рис. 4. Кумулятивный средний удельный баланс для 9 разных горных районов мира за 1980–2001 гг.: 1 — Каскадные горы (2 ледника), 2 — Аляска (2 ледника), 3 — Анды (1 ледник, 1980–2000 гг.), 4 — Шпицберген (2 ледника), 5 — Скандинавия (8 ледников), 6 — Альпы (9 ледников), 7 — Алтай (3 ледника), 8 — Кавказ (1 ледник), 9 — Тянь-Шань (2 ледника)

With the exception of maritime regions (e.g. Alaska, Scandinavia), cumulative trends for the individual mountain ranges (Fig. 4) show continued mass loss since the beginning of the period observed (1980–2001). A special case is the measurements series from the Andes, here, only one glacier is considered (Echaurren Norte, Chile) which is strongly influenced by the ENSO-phenomena. Therefore, this series has to be interpreted carefully in view of possible climatically induced trends (Fig. 4).

In summary, mean annual loss in ice thickness of mountain glaciers during 1980–2001 amounts to approximately -0.3 m w.e. per year, resulting in a total thickness reduction of approximately 6 to 7 m of ice since 1980 (see Fig. 3, b).

Extraordinary situation in Central Europe during 2003

Weather. In the following section information comes, if not stated differently, from reports of the Swiss Federal Institute for Snow and Avalanche Research [19] and the Swiss National Weather Service [12, 13]. Location of the place names mentioned in the text are shown in Fig. 5.

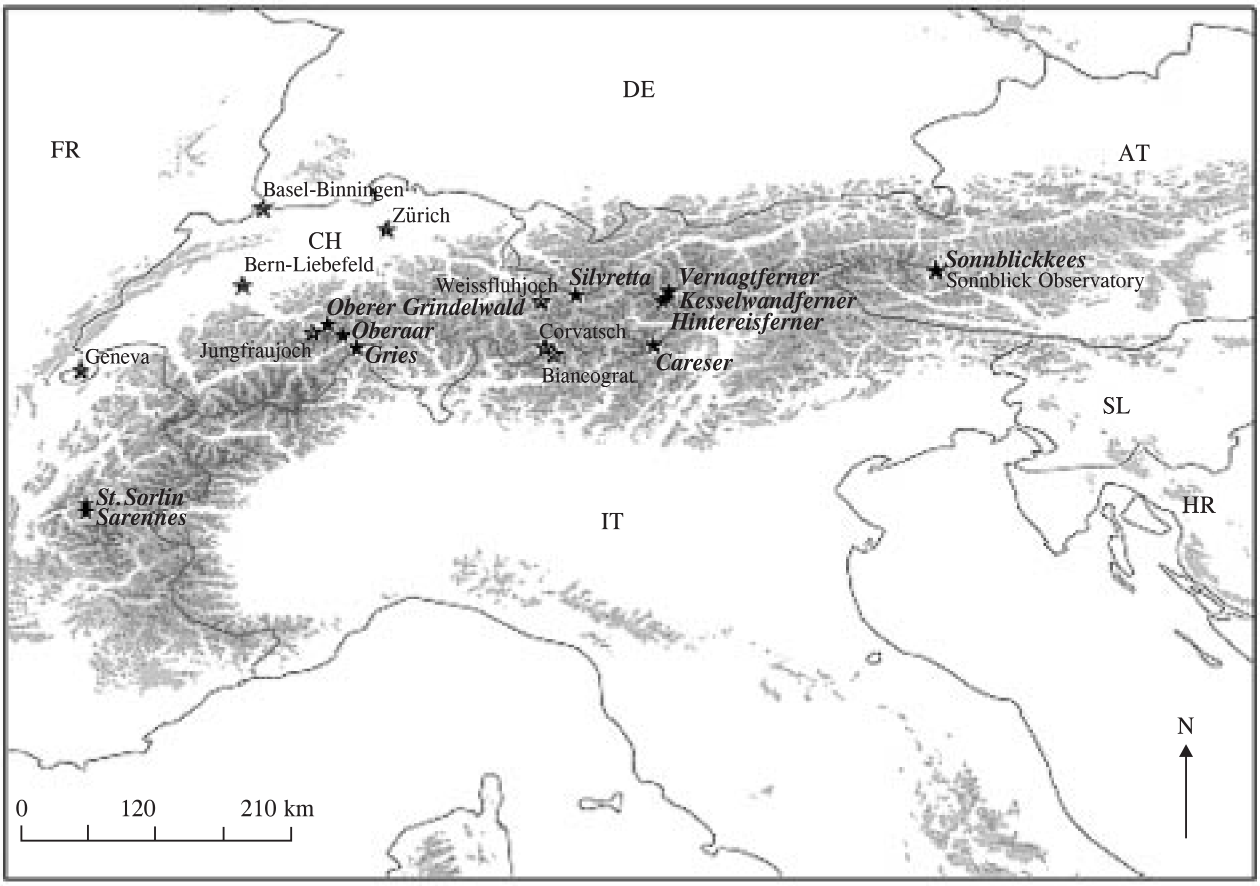

Fig. 5. Greater Alpine Region with the locations named in the text. Black stars represent glaciers. Countries labelled according to the ISO 2-digit country code. Country boundaries provided by ESRI. Background: European HYDRO1k-DEM, elevations above 1000 m are shaded in grey. Source: Land Processes Distributed Active Archive Center (LP DAAC), U.S. Geological Survey's EROS Data Center, http://edcdaac.usgs.gov

Рис. 5. Большой Альпийский регион, показаны места, упомянутые в тексте. Черными звездочками показаны ледники. Названия стран помечены в соответствии с двухзначным кодом стран ISO. Границы стран даны по данным ESRI. Фоновая карта: Европейская ЦМР HYDRO1k-DEM, области выше 1000 м оттенены серым цветом. Источник: Распределенный активный архивный центр по процессам суши (LP DAAC), Центр данных EROS Геологической службы США, http://edcdaac.usgs.gov

In the Alps, winter 2002/2003 started unusually early with snow fall down to 600 m by the end of September. In October the snow line shifted up- and downslope due to changing supply of warm and cold air mass into the Alps. November was characterized by a series of orographic upslope precipitation situations, bringing snow fall far above the average. At the Sonnblick Observatory (3107 m a.s.l., Austria) measured snow fall was three times higher than average, resulting in a total snow height of 2.8 m within 23 precipitation days [16].

After a fair weather period in January with temperatures of up to +4°C at 2000 m at the northern Alpine ridge, repeated snow falls resulted in large snow heights by the beginning of February. The amount of fresh snow fallen by February 6th exceeded the corresponding amount of the extraordinary winter 1999 (known in the Alps as "avalanche winter" due to the large amount of serious avalanche accidents). January and February were cold and predominantly poor in precipitation, especially south of the Central Main Alpine Ridge [16].

After February 6th, no more snow fall events worth mentioning occurred until the beginning of April. February has been registered as the second or third most sunny February during the 103 years of measurements. According to snow records in Switzerland, March has been the month with the least amount of fresh snow since 1950. Sunshine duration in March reached 160–200% of the long-time mean. By mid-March a temperature rise of 12–15°C resulted in an uplift of the 0°C-isotherm to altitudes between 3100 and 3400 m. April started with the passage of a cold front bringing a cooling and snow fall down to the lowlands. With the intensive sunshine und the mild temperatures by the end of April snow melting and rising of the snowline continued rapidly. Normally, altitudes around 1500 m become snow free between mid- and end of May. In 2003 this happened already between mid- and end of April (Fig. 6 for evolution of the thickness of the snow pack in the Swiss Alps during spring 2003).

In the last days of April and the first ones of May, a second Sahara dust event occurred (the first one dating from mid-November). This dust, mixed with pollen and other pollution particles, led to an impressive discolouration of the snow.

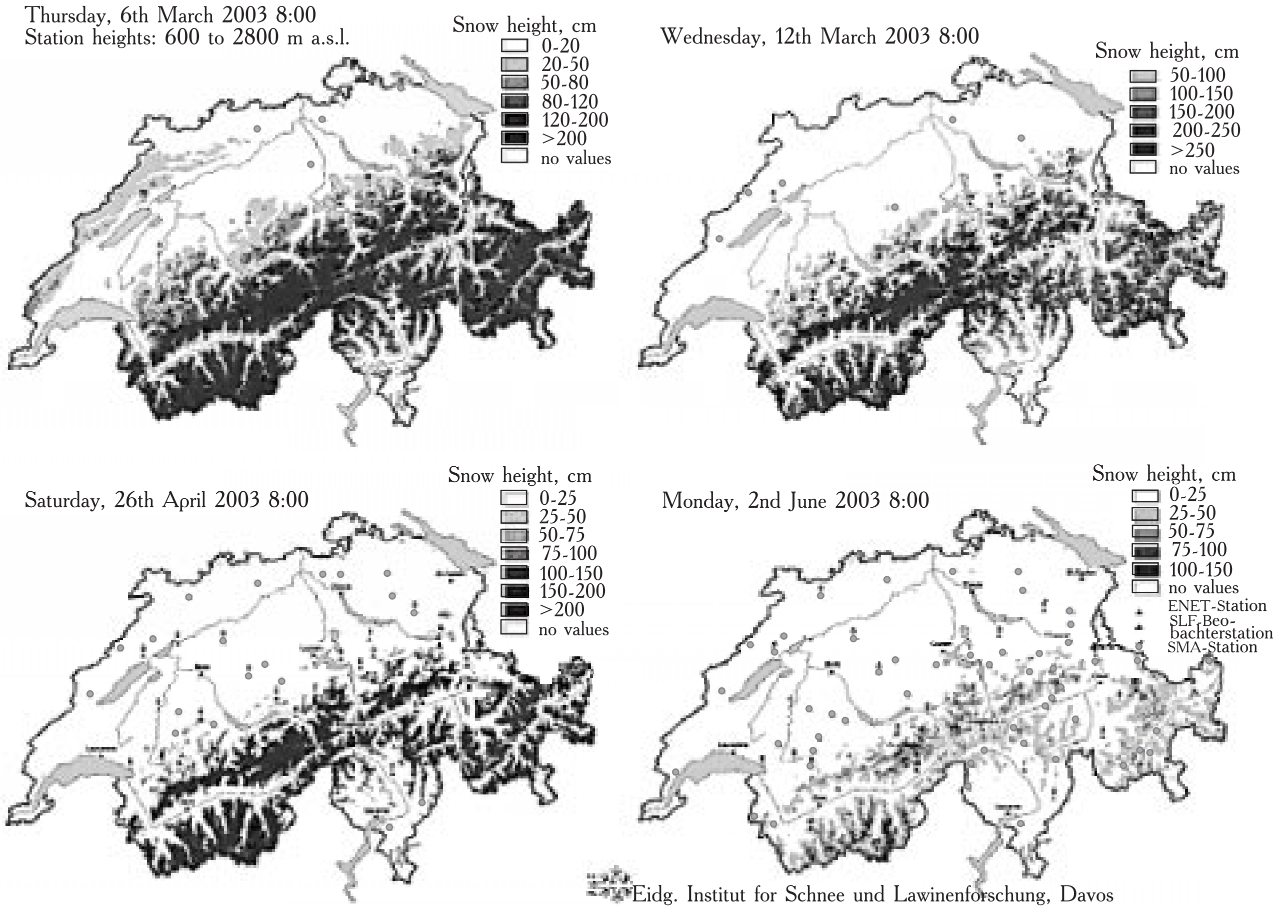

Fig. 6. Snow heights in Switzerland in March, April and June 2003 [19]. Snow heights are interpolated on actual terrain from automatic measurements and measurements by observing persons. Figures kindly provided by the Swiss Federal Institute for Snow and Avalanche Research

Рис. 6. Толщина снега в Швейцарии в марте, апреле и июне 2003 г.[19]. Толщина снега интерполирована по данным автоматических и ручных измерений с учетом реального рельефа местности. Рисунки любезно предоставлены Швейцарским федеральным институтом исследований снега и лавин

At the station Weissfluhjoch (2540 m a.s.l.), Switzerland, daily snow heights have been measured since 1936 (Fig. 7). In November 2002, total snow height reached almost the upper range of the corresponding long-term measurements. On February 8th 90% of maximum snow height of the past 67 years could still be found. The situation changed drastically during the following months: since 1936 there had been more snow at the end of May than in 2003 in 61 winters (rank 62 of 67). On the 1st of June only 34% of the corresponding long-term maximum snow depth were left. Finally, the observation site became snow free on the 14th of June. This is approximately six weeks earlier than on average.

After the unusually warm March and May, which in many regions had been the warmest May since the start of the measurements, the summer 2003 was marked by a record-breaking heat-wave, with its centre over France and Switzerland, that affected the whole European continent. The summer was dominated by anticyclonic influences, while clouds- and rain-bringing west winds rarely reached the Alps.

Fig. 8a [18] shows the temperature anomaly during the summer months June, July and August (JJA) with respect to the 1961–1990 mean, based on ERA-40 reanalysis data and operational meteorological analysis data. Monthly and seasonal temperature data from four stations in Switzerland (Basel-Binningen, Geneva, Bern-Liebefeld and Zurich) representative for the north-western foothills of the Alps were analyzed for the period 1864–2003. In 2003, temperatures in June, August and during the three summer months (JJA) were far off the distribution of 1864–2002 (Fig. 8b, d, e) [18]. The previous record holder for JJA was, for instance, 1947 with a temperature anomaly of $T'=2.7$°C (with respect to the 1864–2000 mean) [18]. The corresponding value for 2003 is $T'=5.1$°C and this amounts to an offset of 5.4 standard deviations from the mean [18]. Corresponding values of individual months are listed in Fig. 8b-e.

Record June temperatures at Sonnblick Observatory (3107 m a.s.l., Austria) were between 5.8 and 6.7°C above the mean of 1961–1990 [16]. In August, all daily mean temperatures at that location were above the norm and the monthly mean reached extraordinary 4.8°C [16]. In the Swiss Alps, recorded mean daily temperatures at Jungfraujoch (3580 m a.s.l.) amounted to 3°C and to 5.5°C at Corvatsch (2690 m a.s.l.) [19]. Using these values, calculated mean altitude of the 0°C-isotherm in July and August was around 4000 m.

The hot summer period ceased by the end of August when south-western winds brought warm and very moist air masses towards the Alps. After almost three months of drought heavy precipitation set in, propagated to the northern Alpine rim and lowered the snow line down to approximately 2000 m. The final end of the summer came by the beginning of October with a cold front from the west turning into a north-wind situation with orographic upslope precipitation, resulting in heavy snow fall down to 1000 m.

Overall, the year 2003 was 1.6 to 2°C warmer then the mean of 1961–1990. In some regions it was the warmest year that has ever been measured since the beginning of the records in 1880. With the extreme sunny months March and June, in the mountains also February, the yearly sunshine reached 115 to 130% of the mean of 1961–1990. It was the most sunny year since 1949, in some regions even since the beginning of the series in 1880. In addition, 2003 was one of the ten driest years of the past 103 years.

Glaciers. As described above, the winter snow cover was below average snow height. Already in May the snow was exposed to strong melting. Saharan dust, pollen and other pollution particles accumulated during ongoing melting and led to an albedo-feedback that enhanced the already strong ablation. Melting periods lasting for weeks without interruption resulted in extraordinary ablation values in 2003. Due to the early start of the ablation season, melting was not only strong but also of long duration. For the Vernagtferner in Austria, for example, it

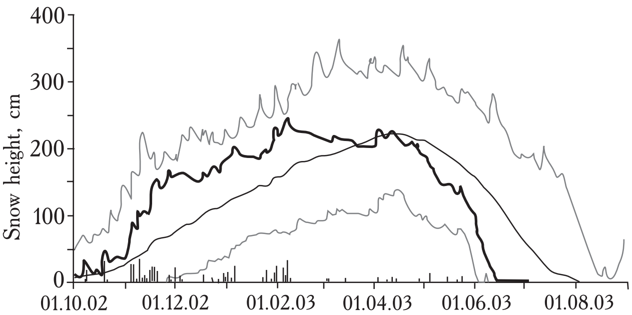

Fig. 7. Development of snow height during the hydrological year 2002/03 at the observation site on Weissfluhjoch (2540 m a.s.l.), Switzerland. Every morning snow height (bold line) and amount of fresh snow (black bars) are measured. Upper and lower lines mark the maximum and minimum snow heights since 1936, the grey line in the middle represents the long-term mean since 1936 [19]. Figure kindly provided by the Swiss Federal Institute for Snow and Avalanche Research

Рис. 7. Изменение толщины снега в течение 2002/03 г. на площадке наблюдений станции Вайсфлуйох (2540 м над ур. моря), Швейцария. Каждое утро измерялась толщина снега (жирная линия) и количество свежевыпавшего снега (черные столбики). Серые линии сверху и снизу показывают максимальную и минимальную толщину снега с 1936 г., а посредине — средние многолетние значения с 1936 г. Рисунок любезно предоставлен Швейцарским федеральным институтом исследований снега и лавин

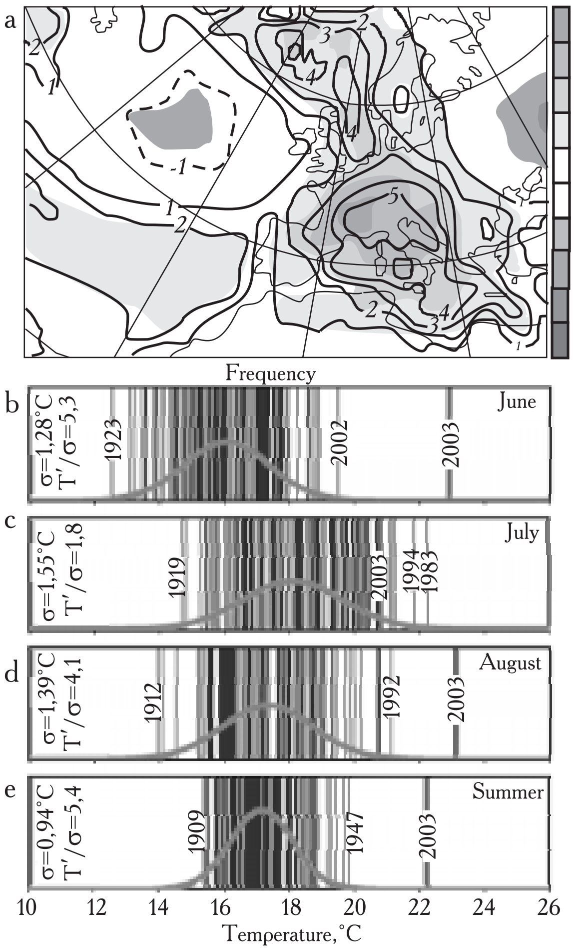

Fig. 8. Characteristics of the summer 2003 heat-wave [18]. a — JJA temperature anomaly with respect to the 1961–1990 mean. Shading shows temperature anomaly [°C], bold contours display anomalies normalized by the 30-year standard deviation. b–e) Distribution of Swiss monthly and seasonal summer temperatures for 1864–2003. The fitted gaussian distribution is indicated by the grey line. The values in the lower left corner of each panel list the standard deviation (σ) and the 2003 anomaly normalized by the 1864–2000 standard deviation (T'/σ). Figure reprinted with permission of the authors from [18]

Рис. 8. Характеристики волны летнего тепла 2003 г. [18]: а — температурная аномалия в июне-августе по отношению к среднему значению за 1961–1990 гг. Фоном разной интенсивности показана температурная аномалия, жирными изолиниями — аномалии, нормализованные по стандартному отклонению за 30 лет; b–e — распределения месячных и сезонных летних температур в Швейцарии за 1864–2003 гг. Подобранное гауссово распределение показано серой линией. Значения в нижнем левом углу каждого графика показывают стандартное отклонение (σ) и аномалию 2003 г., нормализованную по стандартному отклонению за 1864–2000 гг. (T'/σ). Рисунок публикуется с разрешения авторов [18]

Fig. 9. Biancograt, Switzerland, reaching from approximately 3600 m (bottom of figures) to Piz Alv, 3995 m (top of figures). Left picture taken on August 17th 2002, right picture taken on August 9th 2003. Both pictures kindly provided by C. Rothenbühler

Рис. 9. Вид Бианкограт (Швейцария) в диапазоне высот примерно от 3600 м (нижняя часть фотографий) до 3995 м, Пиц-Алв (верхняя часть фотографий). Левый снимок сделан 17 августа 2002 г., правый — 9 августа 2003 г. Обе фотографии любезно предоставлены К. Ротенбюлером

lasted over 100 days, compared to the usual 50 to 60 days [20]. Ablation stake measurements at the tongues of Oberer Grindelwaldgletscher (1470 m a.s.l.) and Oberaargletscher (2340 m a.s.l.), Switzerland, showed an ice loss of approximately 13 m w.e. and 7 m w.e., respectively. Corresponding values in summer 2002 were 6–7 m w.e. at Oberer Grindelwaldgletscher and approximately 3 m w.e. at Oberaargletscher [11].

The snow line rose above the maximum elevations of many glaciers, leaving them without or only with minor accumulation areas. Fig. 9 shows the Biancograt in Switzerland, a ridge famous among mountain climbers. In August 2003 only its main ice ridge was left (Fig. 9, right). Snow, firn and ice that usually cover large parts of the neighbouring rock walls (Fig. 9, left) had largely melted away.

Reporting period for the «Glacier Mass Balance Bulletin, № 8 (2002–2003)» issued by the WGMS ends in fall 2004. Therefore, only preliminary mass balance data is available for the years 2002 and 2003. However, first rough estimates indicate an average loss in thickness of Alpine glaciers in 2003 of almost -3 m w.e. (Fig. 10).

Assuming a total Alpine glacierized area of 2909 km^2 in 1970/80 [5], relative loss in glacier size from 1973–1998/99 of 20% [17], an ice loss of almost -3 m w.e. in 2003 and a total ice volume of approx. 75 km^3 before 2003 (Paul, personal communication), estimated total glacier volume loss in 2003 corresponds to roughly 5–10% of the ice volume still present before 2003.

Discussion

Mass balances 1980–2001. As shown above, mean annual ice thickness loss of mountain glaciers is close to one third of a meter per year during the period 1980–2001. This results in a total thickness reduction of approximately 6 to 7 metres of ice since 1980. The spatially and regionally fairly well distributed sample of glaciers considered suggests that these values are, indeed, of worldwide representativity for mountain regions.

The spectacular loss in length, area and volume of mountain glaciers during the 20th century is a major reflection of the fact that rapid secular change in the energy balance of the earth's surface is taking place on a global scale [6]. The rate of this change is broadly consis-

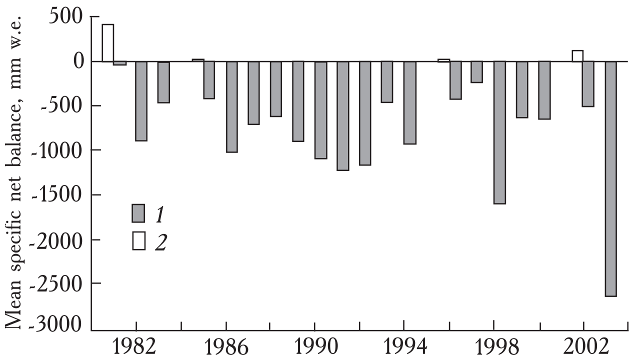

Fig. 10. Mean specific net balance of nine mountain glaciers in the European Alps for the period 1980—2003. The means are calculated using the annual mass balance of the following glaciers: St. Sorlin and Sarennes (France), Silvretta and Cries (Switzerland), Sonnblick, Vernagtferner, Kesselwandferner and Hintereisferner (Austria), Careser (Italy); 2002, 2003, incomplete sample, series subject to change; 1 — negative balances, 2 — positive balances

Рис. 10. Средний удельный чистый баланс 9 горных ледников Европейских Альп за 1980—2003 гг. Средние значения рассчитаны с использованием годовых величин баланса массы следующих ледников Альп: Сен-Сорлен и Саренс (Франция), Сильвретта и Грис (Швейцария), Сонбликс, Фернагтфернер, Кесельвандфернер и Хинтерайсфернер (Австрия),ココ Каресе (Италия). За 2002 и 2003 гг. данные неполны (ряды могут быть уточнены); 1 — отрицательные значения, 2 — положительные значения

tent with the estimated radiative forcing and changes in sensible heat as calculated with numerical climate models [6]. While the beginning of this rapid secular glacier retreat was probably little affected by human activity, there is little doubt that the current evolution contains an increasing anthropogenic influence [6].

Central Europe 2003. In the Alps, the beginning of 2003 was characterized by high accumulation lasting until the end of February. After that Alpine weather was dominated by anticyclonic weather types which are characteristic for high temperatures, high short-wave radiation, few clouds and low precipitation. This reversed the above-average accumulation from the first half of the winter into low snow heights in late winter, fast melting in spring and an unusually early start of the ablation season. The ablation period lasted for more than three months, again dominated by stationary anticyclonic systems over Europe. The snow line rose above the top of many glaciers, resulting in extensive melting of the firn layers. Together with the accumulated pollution particles this did not only enhance melting in 2003, but might also influence ablation in the coming years due to a reduced albedo of the glacier surfaces.

Mass balances of Hintereisferner and Sonnblickkees (both in Austria) and weather type classifications were analysed for the period 1966—1995 [8]. The author shows that for extremely negative years anticyclonic weather types dominated the accumulation and especial-

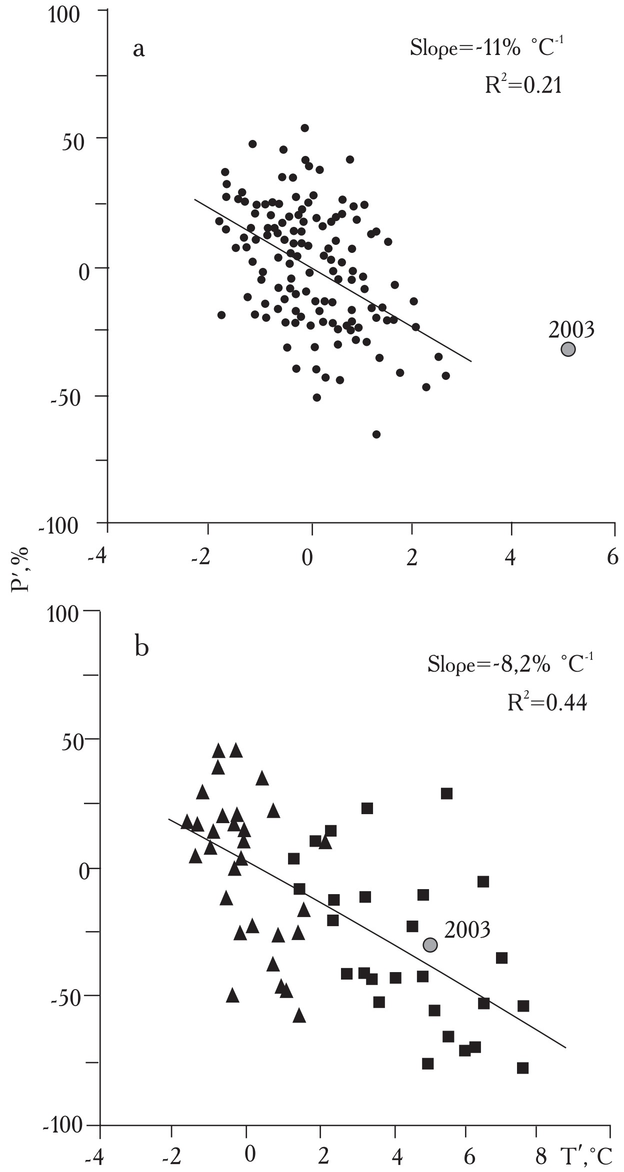

Fig. 11. Scatter diagrams showing summer temperature and precipitation anomalies for northern Switzerland. a) Long-term (1864—2003) station data with respect to 1961—1990 mean. b) Climate change simulation, control run (1961—1990, triangles) and scenario run (2071—2100, squares) with respect to control run mean. The bold circles show the observations for JJA 2003. The regression lines in a) and b) are based on 1864—2002 data and combined control and scenario run data, respectively. Figure reprinted with permission of the authors from [18]

Рис. 11. Диаграммы рассеяния, показывающие аномалии летних температур и осадков для северной Швейцарии: а — многолетние (1864—2003 гг.) данные по станциям, аномалии взяты по отношению к средним значениям за 1961—1990 гг; b — модельные данные климатических изменений, контрольный расчет (1961—1990 гг., треугольники) и сценарный расчет (2071—2100 гг., квадратики), приведенные к среднему значению контрольного расчета. Жирные кружки соответствуют наблюдениям за июнь-август 2003 г. Линии регрессии основаны на данных 1864—2002 гг. и объединенных данных контрольного и сценарного расчетов, соответственно. Рисунок публикуется с разрешения авторов [18] ly the ablation period of the two glaciers. Summer air temperature, winter precipitation and summer radiation balance may be used to parameterize glacier mass balance [e.g. 10, 15]. Such studies can help to understand inter-annual and regional dependence of glacier mass balance and general weather situations. However, to analyse intra-annual sensitivity of glacier mass balance to individual energy balance parameters the use of mass balance models is needed [e.g. 2, 9, 14].

The mean Alpine net balance in 2003 of almost -3 m w.e. (cf. above) is nearly twice as much as during the previous record year of 1998 (-1.6 m w.e.) and roughly five times more than the Alpine average loss of -0.6 m w.e. per year since 1980. In addition, this value is one order of magnitude higher than the global mean annual net balance of -0.3 m w.e. recorded during the already exceptionally warm period 1980–2001 (Fig. 3b, Figs. 4, 10).

The importance of the 2003 event in view of predicted climate change scenarios. The question if the extraordinary summer 2003 was only a maverick of today's climate or already a foreboding of things to come, is hard to answer. Therefore, possible future European climate was simulated by scientists from the ETH Zürich, using a regional climate model in a scenario with increased atmospheric greenhouse-gas concentrations and compared to results of long-term (1864–2003) station data from northern Switzerland, with respect to 1961–1990 (Fig. 11) [18].

Fig. 11 demonstrates that in terms of temperature and precipitation the climatic conditions in JJA 2003 were not unlike those simulated by the scenario run for the period 2071–2100. For northern Switzerland, the 2003 observation is located approximately in the middle of the scenario data points (Fig. 11b). Thus, the RCM simulations suggest that (under the given scenario assumptions) about every second summer could be as warm or even warmer (and dry or even dryer) than 2003 towards the end of the century [18]. Dramatic consequences of this scenario for glacier mass changes would have to be expected for the future. Volume losses in the order of 5–10% during one year (cf. above) would not constitute exceptional values but could occur frequently. Such developments would even exceed scenarios which are based on glacier shrinking rates of the last decades (25% volume loss in the last 25 years; loss of roughly two thirds of the original volume since 1850 [5]) that imply that less than 50% of the glacier volume still present in 1970/80 would remain in 2025 and only about 5–10% in 2100 [5].

Conclusion

Glacier mass balance, as the direct, undelayed signal of climate change, is among the most important parameters within global climate-related observation systems. Thus, efforts must be undertaken to resume interrupted series and to maintain and extend the currently existing worldwide observation network.

First results of the comparison of mass balance measurements from the extraordinary year 2003 and the Alpine and global mean implies that glacier melt continues at a considerable and most probably accelerating rate. The summer heat wave in 2003, mainly responsible for the extreme ice loss reported and analysed above, was an European event. However, this summer and its impact on glaciers may well serve as case study for a possible future climate and could therefore be of worldwide interest.

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Meanwhile, the final values of the Alpine mass balances are available for all nine glaciers concerned [7]. The corrected values of the resulting mean specific net balance of the European Alps for 2002 and 2003 are -0.8 m w.e. and -2.5 m w.e., respectively. The value of 2003 is slightly smaller then the previously estimated value of nearly 3 m w.e.(see Text and Fig. 10). This does, however, not change the general conclusions that glacier melt in 2003 was extraordinary in the European Alps, and that the general decrease of global glacier mass continues at a fast, and probably accelerated rate.

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Измерения баланса массы ледников мира: общие тренды и первые результаты исследований необычной ситуации 2003 г. в Центральной Европе

Ледники служат одним из ключевых индикаторов происходящих изменений климата. Помимо изменений длины ледников, где климатический сигнал отражается с запозданием, в фильтрованном и одновременно усиленном виде, особое значение имеют данные о балансе их массы, где этот сигнал отражается непосредственно и без какой либо задержки. Всемирная служба слежения за ледниками (Цюрих, Швейцария) собирает, стандартизирует и публикует каждые два года данные измерений баланса массы ледников мира. В настоящей статье рассматриваются тренды баланса массы ледников мира, в частности, за 1980–2001 гг. и для чрезвычайно жаркого и сухого лета 2003 г. в Центральной Европе, которое привело к потере 5–10% объема ледников Альп. Моделирование будущих температурных сценариев для северной Швейцарии дает основание полагать, что к концу текущего столетия каждое второе лето может быть столь же жарким или еще жарче (и таким же сухим или суше) [18]. Необычное лето 2003 г. наблюдалось в Центральной Европе, но такая ситуация может служить типичным примером возможного климата в будущем и в глобальном масштабе.